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A METHOD FOR ARRAYING YAGI-DISK ANTENNAS

by Fred B. Beck

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A METHOD FOR ARRAYING YAGI-DISK ANTENNAS

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SUMMARY

This paper is concerned with the problem of arraying yagi-disk (disk-on-rod) surface-wave structures having large spacings between the elements of the array - that is, spacings greater than a wavelength at the design frequency. It is shown that symmetrical arrays having sidelobe levels less than -12 dB below the main beam of the array can be designed by using simple array theory and the knowledge of a single-element pattern. It is significant to note that off-principal-plane sidelobes are less than those in the principal plane and that no excessive energy is lost in spurious sidelobes.

INTRODUCTION

The amplitude of the electric field as a function of radial distance perpendicular to the axis of a 6-wavelength yagi type of antenna has been determined. (See ref. 1.) Mutual coupling between shorter elements as a function of spacing between elements has also been determined. (See ref. 2.) From these results it appears that the design of an array of yagi antennas based on simple array theory will require interelement spacings, a wavelength or greater, to obtain a coupling value which may be neglected.

Since interelement coupling indicates that the spacing between elements be greater than a wavelength, the problem of grating lobes in the far-field pattern of the array is introduced. If these grating lobes are not properly controlled, they may be nearly as large in amplitude as the main lobe of the array.

The purpose of this paper, therefore, is to point out experimental results which substantiate the following conclusions:

(1) Arrays of yagi-disk antennas can be designed with element spacings which simultaneously fulfill the requirements of negligible interelement coupling and grating-lobe suppression.

(2) For the designs considered, there are no off-principal-plane sidelobes or grating lobes higher than those in the principal planes.

(3) The gain for arrays of yagi-disk elements satisfying the previous conclusions (1) and (2) can be accurately calculated from a knowledge of the gain of a single element.

SYMBOLS

A	array factor
b	length of ground plane
D	disk diameter
d	distance between elements
E	element pattern
F_o	design frequency
h	height of feed bucket above ground plane
i,k	elements and rows in yagi-disk arrangement
$j = \sqrt{-1}$	
L	total length of yagi element
l_1	distance from ground plane to feed dipole
l_2	distance from feed dipole to first disk
N_1	number of elements in a row
N_2	number of rows of elements
$P(r,\phi,\theta)$	coordinates describing point at which field is measured
S_d	spacing between disks
S_f	spacing between feed dipoles
$S_{i,k}$	projected distance between ith element in kth row and reference element
X,Y,Z	coordinate axes
δ	off-principal-plane angle
λ	wavelength
λ_o	wavelength at design frequency
Φ	array pattern

ϕ azimuthal angle normal to plane of array

$\psi_{i,k}$ phase difference of ith element in kth row with respect to reference element

YAGI-DISK ELEMENT

The yagi-disk antenna used as the basic array element is shown in figures 1 and 2. Considerable work has previously been done on the design of antennas of this type. (See ref. 3.) For the particular element design eventually chosen for the array, the beam width and gain characteristics over the frequency range of interest (2.2 Gc to 2.4 Gc) were less than 40° and greater than 12 dB, respectively. (See ref. 4.)

When short elements are used ($2\lambda_0$ to $4\lambda_0$), the beam width and gain are essentially determined by the yagi structures, whereas, the sidelobe levels and sidelobe positions are primarily controlled by the details of the feed network. It has been shown that tailoring of the element pattern can be accomplished by adjusting the feed-dipole spacing S_f, the distance from the dipole to the first disk l_2, and the addition of the feed bucket around the feed network. (See ref. 3.)

ARRAY FACTOR FOR ELEMENT SPACING

In the design of an array of antennas, it is often possible to develop a so-called array factor. If an array factor is to be developed, each element within the array must have like far-field radiation patterns. If an array factor can be determined and if the element pattern can be measured, the array pattern can then be calculated. That is, the array pattern is simply the array factor times the element pattern.

With the use of figure 3, the far-field radiation pattern due to the elements N_1 times the rows N_2 can be expressed as:

$$\Phi = \sum_{k=1}^{N_2} \sum_{i=1}^{N_1} Ee^{j\psi_{i,k}}$$

where

Φ array pattern

E element pattern

$\psi_{i,k}$ phase difference of ith element in kth row with respect to reference element

When simplified and normalized by N_1N_2, the array pattern may be rewritten as follows:

$$\Phi = \frac{E}{N_1N_2} \frac{\sin N_1 \dfrac{\psi_{2,1}}{2} \sin N_2 \dfrac{\psi_{1,2}}{2}}{\sin \dfrac{\psi_{2,1}}{2} \sin \dfrac{\psi_{1,2}}{2}}$$

where Φ/E is the so-called array factor. Its complete derivation can be found in the appendix.

Being able to develop an array factor is advantageous to the design of any array. With this knowledge, it is possible to obtain at least a rough approximation of the far-field pattern without having to measure it. For this approximation, however, it is assumed that little or no coupling exists between elements.

ELEMENT-SPACING CRITERIA

As was stated in the introduction, spacings of a wavelength or greater introduce into the array factor a grating lobe which is equal in magnitude to the main lobe. However, if proper care is taken, the grating lobe may be suppressed by proper tailoring of the element pattern. This principal of grating-lobe suppression is pointedly demonstrated in figure 4. (See also ref. 5.) When the array factor and element pattern are known, the array pattern is derived simply by the product of the two (i.e., the array factor and the element pattern) if interelement coupling is negligible. With a known element pattern, the grating lobe of the array factor can be made coincident with the first sidelobe of the element pattern by adjusting the interelement spacing. This interelement spacing - that is, spacing which makes the grating lobe coincident with first sidelobe of the element pattern - appears sufficient for negligible interelement coupling independent of element length ($2\lambda_o$ to $6\lambda_o$). With the use of these criteria, two linear arrays having 4 and 16 elements, respectively, were designed. That is, the element pattern was measured and the spacing between elements was adjusted so that the grating-lobe position corresponded to the first-element sidelobe position. Calculated patterns, for which it was assumed there was no coupling, along with measured patterns, are given in figure 5. To verify further that coupling is small, measurements of coupling were made between two antennas with the feed dipoles both broadside and end to end. A graph of coupling plotted against separation between antennas can be seen in figure 6.

The interelement spacing could just as well be increased to position the grating lobe to correspond to the position of the null between the main lobe and first sidelobe of the element pattern. This increased spacing would decrease even further the level of the grating lobe in measured array patterns. However, using this approach would make the grating-lobe level very frequency sensitive. In addition, the amplitude of most nulls between the main lobe and first sidelobe of measured elements is not appreciably lower than the amplitude of the first sidelobe.

The interelement spacing could also be decreased to position the grating lobe to correspond to the position of the null between the first and second sidelobes of the element pattern. This change in interelement spacing would also decrease the level of the grating lobe in measured array patterns. With this approach, the problem of interelement coupling and a frequency-sensitive grating lobe is encountered. Since the object is to eliminate interelement coupling, this approach should be used only with great caution.

SIDELOBES OFF THE PRINCIPAL PLANES

It has been shown in the previous section entitled "Element Spacing Criteria" that sidelobes in the principal planes can be reduced to a value equal to or less than -12 dB below the main beam of the array. Of equal importance is the control of off-principal-plane sidelobes. For use in the study of this problem, a symmetrical 16-element array (4 by 4) was designed with the dimensions shown in figure 1. Measurements of the far-field pattern of this array were made at 5° increments of δ, where δ is the off-principal-plane angle shown in figure 3. The results of these measurements, plotted in the form of sidelobe levels as a function of δ, are shown in figure 7 for $0 \leqq \delta \leqq 45^{\circ}$. Since the array is symmetrical, this range of δ defines all cases.

After the far-field pattern of the array was measured at 5° increments of δ, it was observed that there existed only three significant sidelobes on each side of the main lobe. The first sidelobe, and to some extent the second sidelobe, are primarily determined by the array factor. That is, as a function of δ, the element pattern changes only slightly near the main lobe, whereas the array factor changes more than 15 dB within the confines of the main lobe of the element pattern. (For example, see fig. 4.) The third sidelobe appearing in the measured array patterns is the so-called grating lobe. It is dependent upon both the element sidelobes and the array factor. The grating lobe of the array factor changes much more rapidly than the lobes nearer the main lobe, both as a function of azimuth angle ϕ and magnitude. Calculations which used the formula given in the appendix were made on the assumption that the element patterns are identical and independent of δ. Of course, the assumption that the element patterns are identical and independent of δ is not necessarily true, yet the calculated curves in figure 7 show that good agreement is still obtained.

GAIN CONSIDERATIONS

It is possible to predict the gain of a large array of yagi-disk antennas from the knowledge of a single-element gain if mutual coupling is negligible.

The gain of a 16-element (4 by 4) array was calculated on the basis of a known element gain. A comparison of the calculated and measured array gain is given in figure 8. The agreement is indicative of the fact that interelement coupling is negligible and that no excessive energy is lost in spurious sidelobes.

CONCLUDING REMARKS

A design technique for arraying yagi-disk elements has been developed. This technique, based on the pattern of a single element and on simple array calculations, permits array designs of yagi-disk elements which simultaneously fulfill the requirements of negligible interelement coupling and grating-lobe suppression.

In addition, it has been shown that for arrays designed utilizing this technique, accurate prediction of off-principal-plane sidelobes and array gain can be made from the knowledge of a single element. With this knowledge large arrays of such elements can be designed without physical construction of the entire array.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., October 9, 1964.

APPENDIX

DERIVATION OF ARRAY FACTOR

The following derivation is of the array factor for a broadside rectangular (N_1 by N_2) array. If a broadside rectangular array is uniform, it can be considered as a linear array of linear arrays. (See ref. 6.) With the use of figure 3, all elements can be projected to an arbitrary line so that the rectangular array will effectively look like a linear array, as shown in figure 9. For convenience, the arbitrary line chosen is the Z-axis. From the projected positions of the elements and with the element farthest left from the Y-axis as a reference, the distances to the remaining elements from the reference element are as follows. (See fig. 9.)

Row 1: $S_{1,1} = 0$

$S_{2,1} = d \sin \delta$

$S_{3,1} = 2d \sin \delta = 2S_{2,1}$

$\vdots$

$S_{N_1,1} = (N_1 - 1)d \sin \delta = (N_1 - 1)S_{2,1}$

Row 2: $S_{1,2} = d \cos \delta$

$S_{2,2} = d \cos \delta + d \sin \delta = S_{1,2} + S_{2,1}$

$S_{3,2} = d \cos \delta + 2d \sin \delta = S_{1,2} + 2S_{2,1}$

$\vdots$

$S_{N_1,2} = d \cos \delta + (N_1 - 1)d \sin \delta = S_{1,2} + (N_1 - 1)S_{2,1}$

Row 3: $S_{1,3} = 2d \cos \delta = 2S_{1,2}$

$S_{2,3} = 2d \cos \delta + d \sin \delta = 2S_{1,2} + S_{2,1}$

$S_{3,3} = 2d \cos \delta + 2d \sin \delta = 2S_{1,2} + 2S_{2,1}$

$\vdots$

$S_{N_1,3} = 2d \cos \delta + (N_1 - 1)d \sin \delta = 2S_{1,2} + (N_1 - 1)S_{2,1}$

Row N_2: $S_{1,N_2} = (N_2 - 1)d \cos \delta = (N_2 - 1)S_{1,2}$

$S_{2,N_2} = (N_2 - 1)d \cos \delta + d \sin \delta = (N_2 - 1)S_{1,2} + S_{2,1}$

$S_{3,N_2} = (N_2 - 1)d \cos \delta + 2d \sin \delta = (N_2 - 1)S_{1,2} + 2S_{2,1}$

$\vdots$

$S_{N_1,N_2} = (N_2 - 1)d \cos \delta + (N_1 - 1)d \sin \delta = (N_2 - 1)S_{1,2} + (N_1 - 1)S_{2,1}$

With the use of figure 9, the far-field radiation pattern of the array can be expressed as:

$$\Phi = \sum_{k=1}^{N_2} \sum_{i=1}^{N_1} E e^{j\psi_{1,k}} \tag{1}$$

where

Φ	array pattern
E	element pattern
$\psi_{i,k}$	phase difference of ith element in kth row with respect to reference element

and where the $\psi_{i,k}$ can be expressed as follows:

$$\psi_{1,1} = 0 \tag{2}$$

$$\psi_{2,1} = \frac{2\pi d}{\lambda} \cos \phi \sin \delta \tag{3}$$

$$\psi_{3,1} = 2\,\frac{2\pi d}{\lambda} \cos \phi \sin \delta = 2\psi_{2,1} \tag{4}$$

$$\vdots$$

$$\psi_{N_1,1} = (N_1 - 1)\frac{2\pi d}{\lambda} \cos \phi \sin \delta = (N_1 - 1)\psi_{2,1} \tag{5}$$

$$\psi_{1,2} = \frac{2\pi d}{\lambda} \cos \phi \cos \delta \tag{6}$$

$$\psi_{2,2} = \frac{2\pi d}{\lambda} \cos \phi \cos \delta + \frac{2\pi d}{\lambda} \cos \phi \sin \delta = \psi_{1,2} + \psi_{2,1} \tag{7}$$

$$\psi_{3,2} = \frac{2\pi d}{\lambda} \cos \phi \cos \delta + 2\,\frac{2\pi d}{\lambda} \cos \phi \sin \delta = \psi_{1,2} + 2\psi_{2,1} \tag{8}$$

$$\vdots$$

$$\begin{aligned} \psi_{N_1,2} &= \frac{2\pi d}{\lambda} \cos \phi \cos \delta + (N_1 - 1)\frac{2\pi d}{\lambda} \cos \phi \sin \delta \\ &= \psi_{1,2} + (N_1 - 1)\psi_{2,1} \end{aligned} \tag{9}$$

$$\psi_{1,3} = 2\,\frac{2\pi d}{\lambda} \cos \phi \cos \delta = 2\psi_{1,2} \tag{10}$$

$$\psi_{2,3} = 2\,\frac{2\pi d}{\lambda} \cos \phi \cos \delta + \frac{2\pi d}{\lambda} \cos \phi \sin \delta = 2\psi_{1,2} + \psi_{2,1} \tag{11}$$

$$\psi_{3,3} = 2\,\frac{2\pi d}{\lambda} \cos \phi \cos \delta + 2\,\frac{2\pi d}{\lambda} \cos \phi \sin \delta = 2\psi_{1,2} + 2\psi_{2,1} \tag{12}$$

$$\vdots$$

$$\psi_{N_1,3} = 2\,\frac{2\pi d}{\lambda} \cos \phi \cos \delta + (N_1 - 1)\frac{2\pi d}{\lambda} \cos \phi \sin \delta$$

$$= 2\psi_{1,2} + (N_1 - 1)\psi_{2,1} \tag{13}$$

$$\psi_{1,N_2} = (N_2 - 1)\frac{2\pi d}{\lambda} \cos \phi \cos \delta = (N_2 - 1)\psi_{1,2} \tag{14}$$

$$\psi_{2,N_2} = (N_2 - 1)\frac{2\pi d}{\lambda} \cos \phi \cos \delta + \frac{2\pi d}{\lambda} \cos \phi \sin \delta$$

$$= (N_2 - 1)\psi_{1,2} + \psi_{2,1} \tag{15}$$

$$\psi_{3,N_2} = (N_2 - 1)\frac{2\pi d}{\lambda} \cos \phi \cos \delta + 2\,\frac{2\pi d}{\lambda} \cos \phi \sin \delta$$

$$= (N_2 - 1)\psi_{1,2} + 2\psi_{2,1} \tag{16}$$

$$\vdots$$

$$\psi_{N_1,N_2} = (N_2 - 1)\frac{2\pi d}{\lambda} \cos \phi \cos \delta + (N_1 - 1)\frac{2\pi d}{\lambda} \cos \phi \sin \delta$$

$$= (N_2 - 1)\psi_{1,2} + (N_1 - 1)\psi_{2,1} \tag{17}$$

$$\begin{aligned}
\Phi = {} & Ee^{j\psi_{1,1}} + Ee^{j\psi_{2,1}} + Ee^{j\psi_{3,1}} + \ldots Ee^{j\psi_{N_1,1}} \\
& + Ee^{j\psi_{1,2}} + Ee^{j\psi_{2,2}} + Ee^{j\psi_{3,2}} + \ldots Ee^{j\psi_{N_1,2}} \\
& + Ee^{j\psi_{1,3}} + Ee^{j\psi_{2,3}} + Ee^{j\psi_{3,3}} + \ldots + Ee^{j\psi_{N_1,3}} \\
& \vdots \\
& + Ee^{j\psi_{1,N_2}} + Ee^{j\psi_{2,N_2}} + Ee^{j\psi_{3,N_2}} + \ldots + Ee^{j\psi_{N_1,N_2}}
\end{aligned} \tag{18}$$

After substitution of equations (2) to (17) into equation (18), equation (18) may then be rewritten as:

$$\Phi = E\Big\{1 + e^{j\psi_{2,1}} + e^{j2\psi_{2,1}} + \ldots + e^{j(N_1-1)\psi_{2,1}}$$

$$+ e^{j\psi_{1,2}} + e^{j\left[\psi_{1,2}+\psi_{2,1}\right]} + e^{j\left[\psi_{1,2}+2\psi_{2,1}\right]} + \ldots + e^{j\left[\psi_{1,2}+(N_1-1)\psi_{2,1}\right]}$$

$$+ e^{j2\psi_{1,2}} + e^{j\left[2\psi_{1,2}+\psi_{2,1}\right]} + e^{j\left[2\psi_{1,2}+2\psi_{2,1}\right]} + \ldots + e^{j\left[2\psi_{1,2}+(N_1-1)\psi_{2,1}\right]}$$

$$\vdots$$

$$+ e^{j(N_2-1)\psi_{1,2}} + e^{j\left[(N_2-1)\psi_{1,2}+\psi_{2,1}\right]} + e^{j\left[(N_2-1)\psi_{1,2}+2\psi_{2,1}\right]} + \ldots + e^{j\left[(N_2-1)\psi_{1,2}+(N_1-1)\psi_{2,1}\right]}\Big\} \quad (19)$$

where

$\psi_{2,1}$ phase difference of 2nd element in 1st row with respect to 1st element in 1st row

$\psi_{1,2}$ phase difference of 1st element in 2nd row with respect to 1st element in 1st row

When like terms are collected and factored out, equation (19) becomes:

$$\Phi = E\Big\{\left[1 + e^{j\psi_{2,1}} + e^{j2\psi_{2,1}} + \ldots + e^{j(N_1-1)\psi_{2,1}}\right]$$

$$+ e^{j\psi_{1,2}}\left[1 + e^{j\psi_{2,1}} + e^{j2\psi_{2,1}} + \ldots + e^{j(N_1-1)\psi_{2,1}}\right]$$

$$+ e^{j2\psi_{1,2}}\left[1 + e^{j\psi_{2,1}} + e^{j2\psi_{2,1}} + \ldots + e^{j(N_1-1)\psi_{2,1}}\right]$$

$$\vdots$$

$$+ e^{j(N_2-1)\psi_{1,2}}\left[1 + e^{j\psi_{2,1}} + e^{j2\psi_{2,1}} + \ldots + e^{j(N_1-1)\psi_{2,1}}\right]\Big\} \quad (20)$$

$$\Phi = E\left\{\left[1 + e^{j\psi_{2,1}} + e^{j2\psi_{2,1}} + \ldots + e^{j(N_1-1)\psi_{2,1}}\right]\left[1 + e^{j\psi_{1,2}} + e^{j2\psi_{1,2}} + \ldots + e^{j(N_2-1)\psi_{1,2}}\right]\right\} \quad (21)$$

Let the terms in the first brackets be u, that is,

$$u = 1 + e^{j\psi_{2,1}} + e^{j2\psi_{2,1}} + \ldots + e^{j(N_1-1)\psi_{2,1}} \quad (22)$$

Then the following simplification may be performed. Multiplying equation (22) by $e^{j\psi_{2,1}}$ yields

$$ue^{j\psi_{2,1}} = e^{j\psi_{2,1}} + e^{j2\psi_{2,1}} + e^{j3\psi_{2,1}} + \ . \ . \ . + e^{jN_1\psi_{2,1}} \tag{23}$$

Subtract equation (23) from equation (22).

$$u - ue^{j\psi_{2,1}} = 1 - e^{jN_1\psi_{2,1}} \tag{24}$$

or

$$u = \frac{1 - e^{jN_1\psi_{2,1}}}{1 - e^{j\psi_{2,1}}} \tag{25}$$

Equation (25) can be factored as follows:

$$u = \frac{e^{j\frac{N_1\psi_{2,1}}{2}}\left[e^{j\frac{N_1\psi_{2,1}}{2}} - e^{-j\frac{N_1\psi_{2,1}}{2}}\right]}{e^{j\frac{\psi_{2,1}}{2}}\left[e^{j\frac{\psi_{2,1}}{2}} - e^{-j\frac{\psi_{2,1}}{2}}\right]} \tag{26}$$

and can be simplified to:

$$u = e^{j\frac{\psi_{2,1}}{2}(N_1-1)} \frac{\sin \frac{N_1\psi_{2,1}}{2}}{\sin \frac{\psi_{2,1}}{2}} \tag{27}$$

Taking the terms in the second pair of brackets of equation (21) and performing the same manipulations as was done for the terms in the first pair of brackets, one obtains the following simplified array pattern formula:

$$\Phi = Ee^{j\frac{\psi_{2,1}}{2}(N_1-1)} e^{j\frac{\psi_{1,2}}{2}(N_2-1)} \frac{\sin \frac{N_1\psi_{2,1}}{2} \sin \frac{N_2\psi_{1,2}}{2}}{\sin \frac{\psi_{2,1}}{2} \sin \frac{\psi_{1,2}}{2}} \tag{28}$$

If the phase is referred to the center point of the array, equation (28) may then be rewritten as

$$\Phi = E \frac{\sin \frac{N_1 \psi_{2,1}}{2} \sin \frac{N_2 \psi_{1,2}}{2}}{\sin \frac{\psi_{2,1}}{2} \sin \frac{\psi_{1,2}}{2}} \tag{29}$$

Thus, the equation for the array pattern can be written

$$\Phi = EA \tag{30}$$

where

$$A = \frac{\sin \frac{N_1 \psi_{2,1}}{2} \sin \frac{N_2 \psi_{1,2}}{2}}{\sin \frac{\psi_{2,1}}{2} \sin \frac{\psi_{1,2}}{2}}$$

Here, A is called the array factor and may be normalized by dividing by $N_1 N_2$.

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λ_o = 5.35 in.

D = 1.30 in.

L = 16.03 in.

S_d = 1.30 in.

S_f = 3.25 in.

l_1 = 1.73 in.

l_2 = 1.30 in.

h = 1.65 in.

b = 6.00 in.

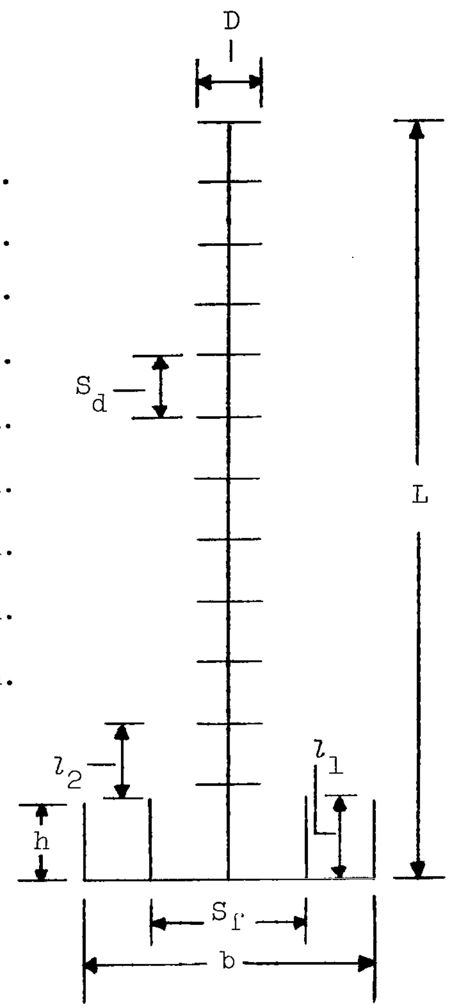


Figure 1.- Diagram of yagi-disk element.

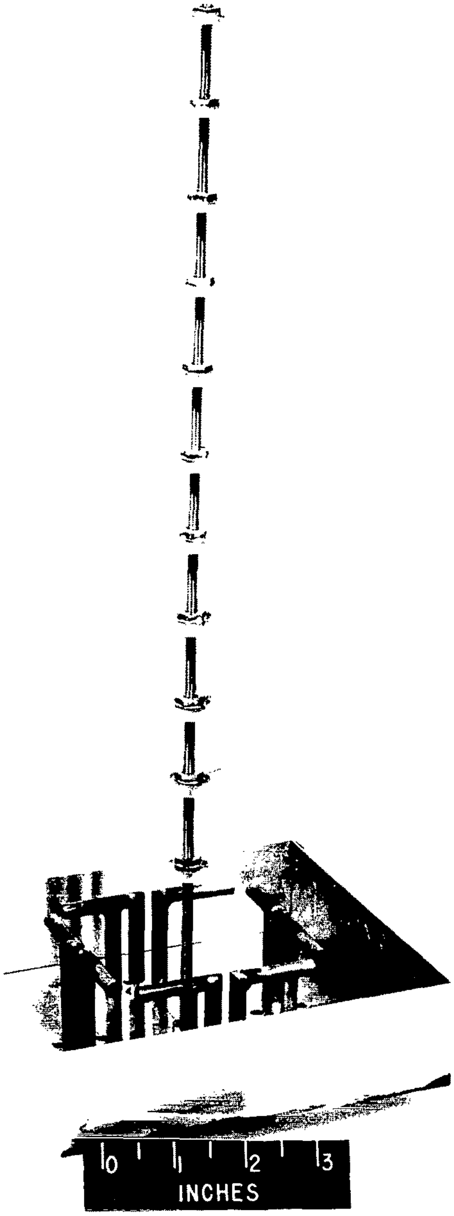


Figure 2.- Yagi-disk element. L-63-9377

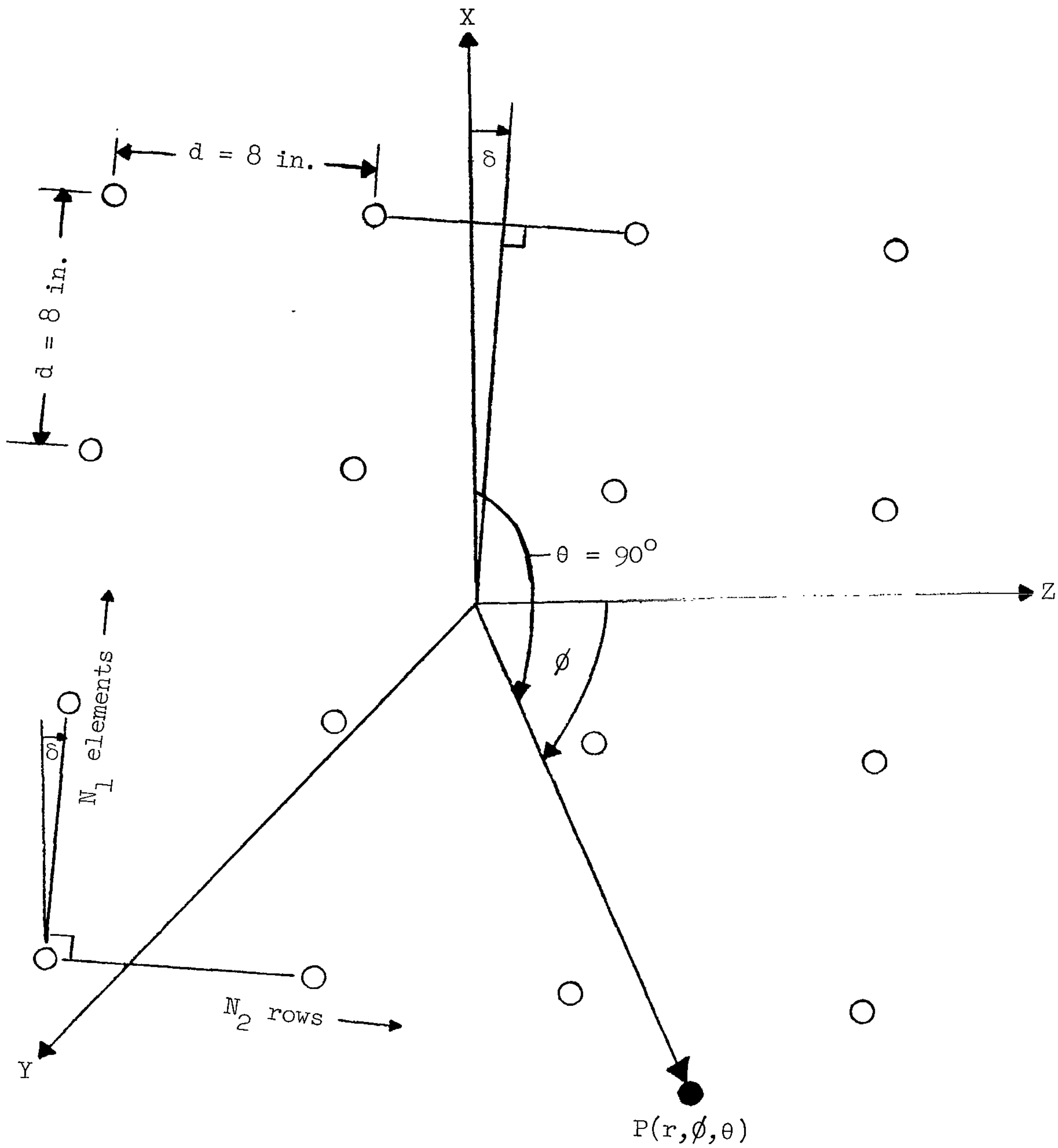


Figure 3.- Yagi array, N_1 by N_2.

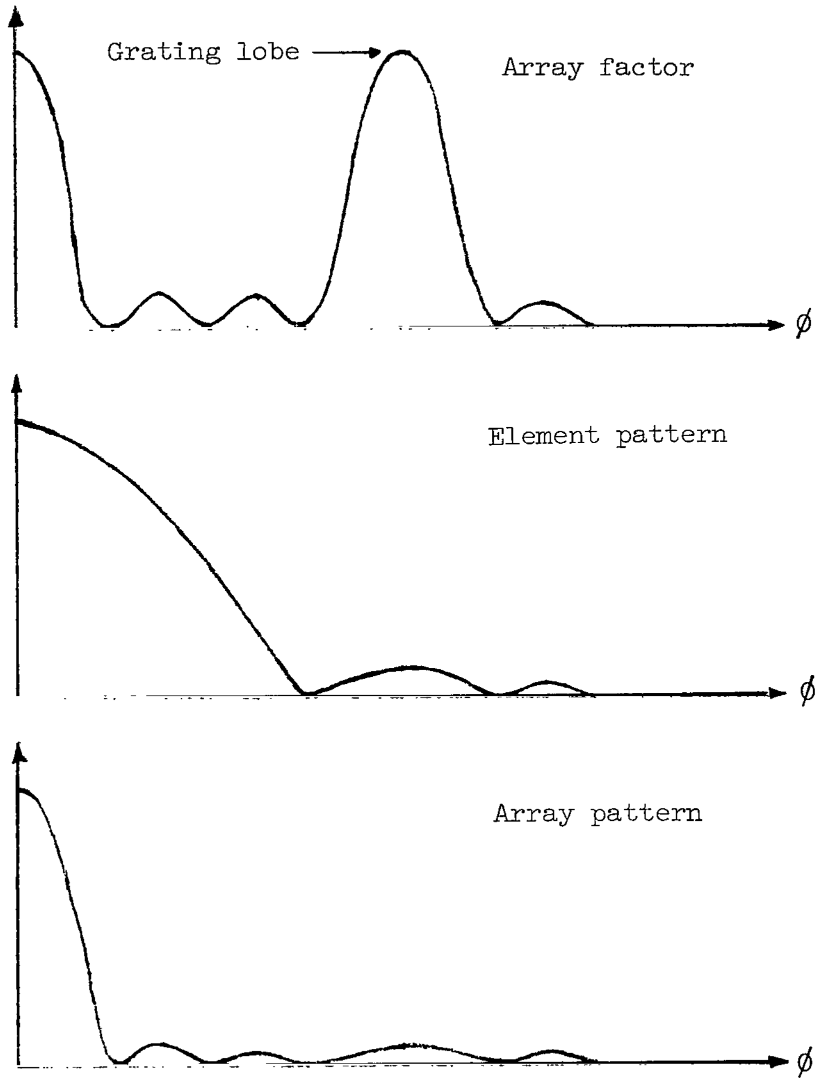
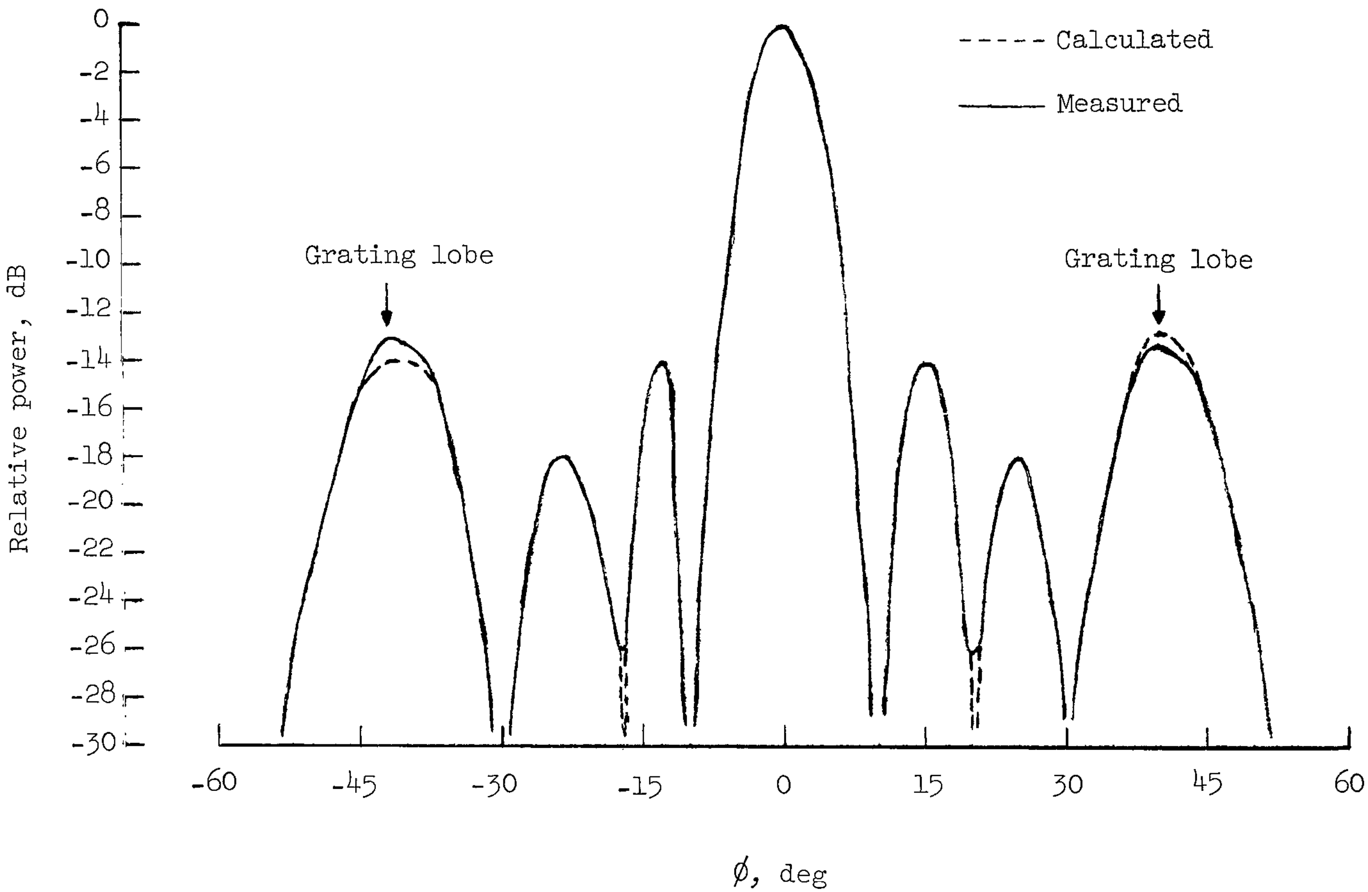
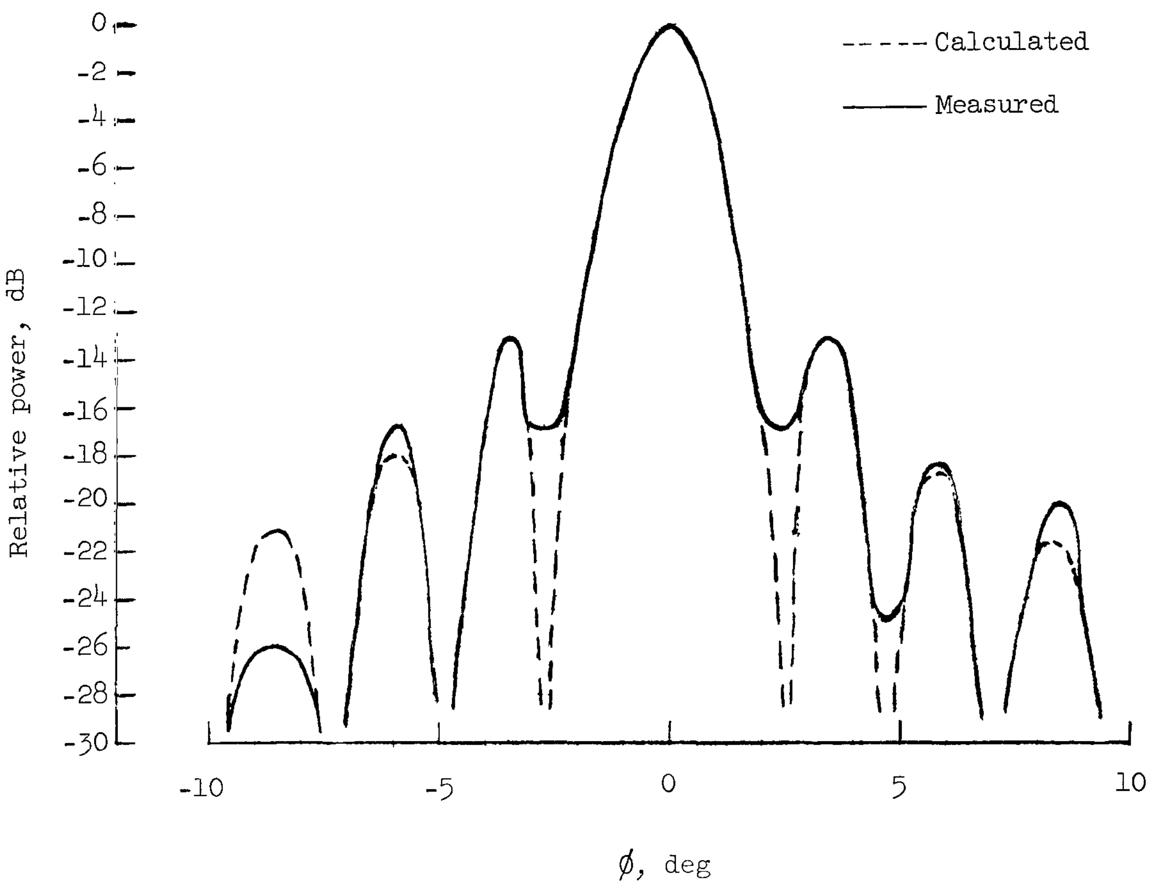


Figure 4.- Principal of grating-lobe suppression. (See ref. 5.)



(a) Four elements.

Figure 5.- Linear array.



(b) Sixteen elements.

Figure 5.- Concluded.

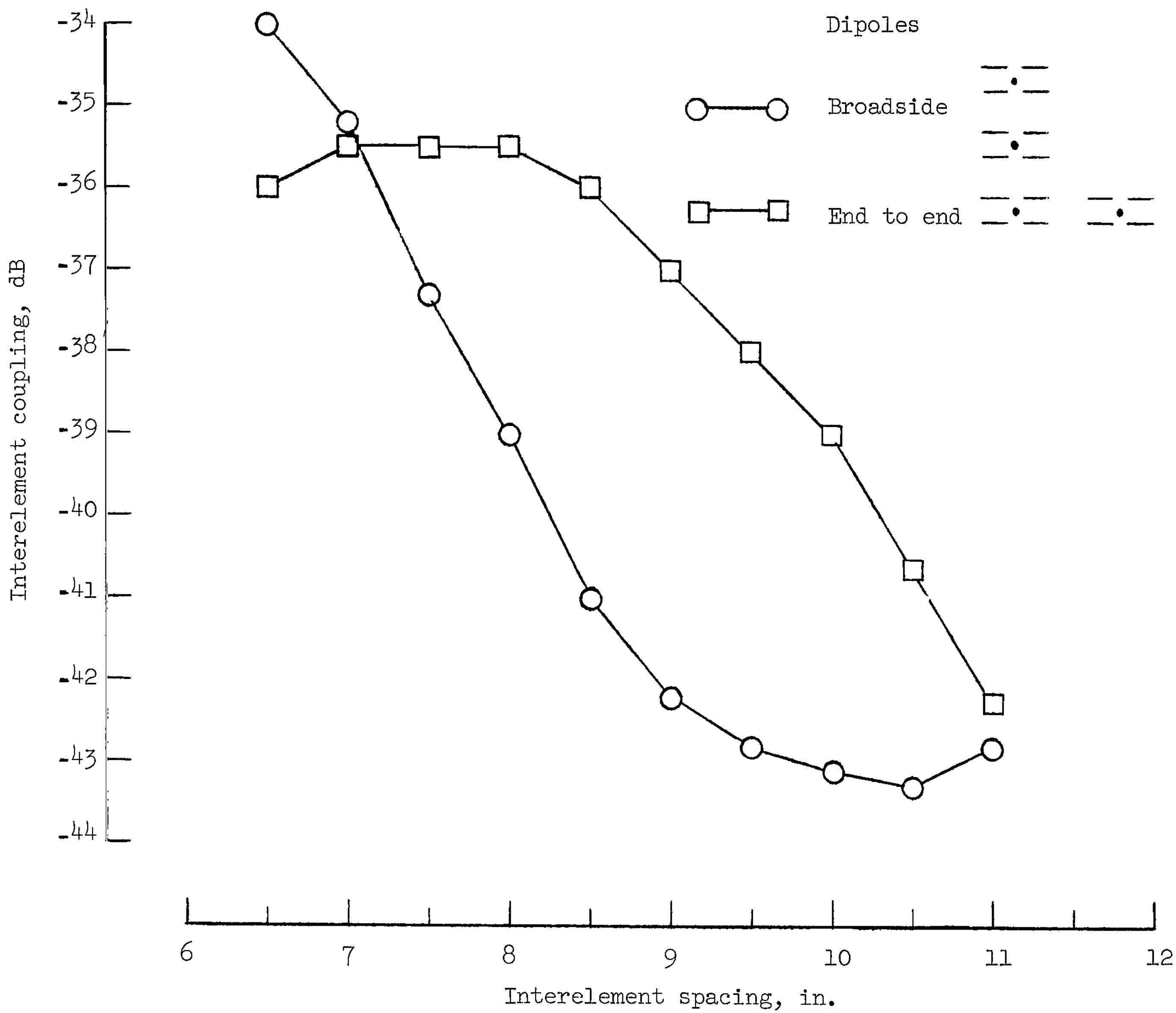


Figure 6.- Interelement coupling.

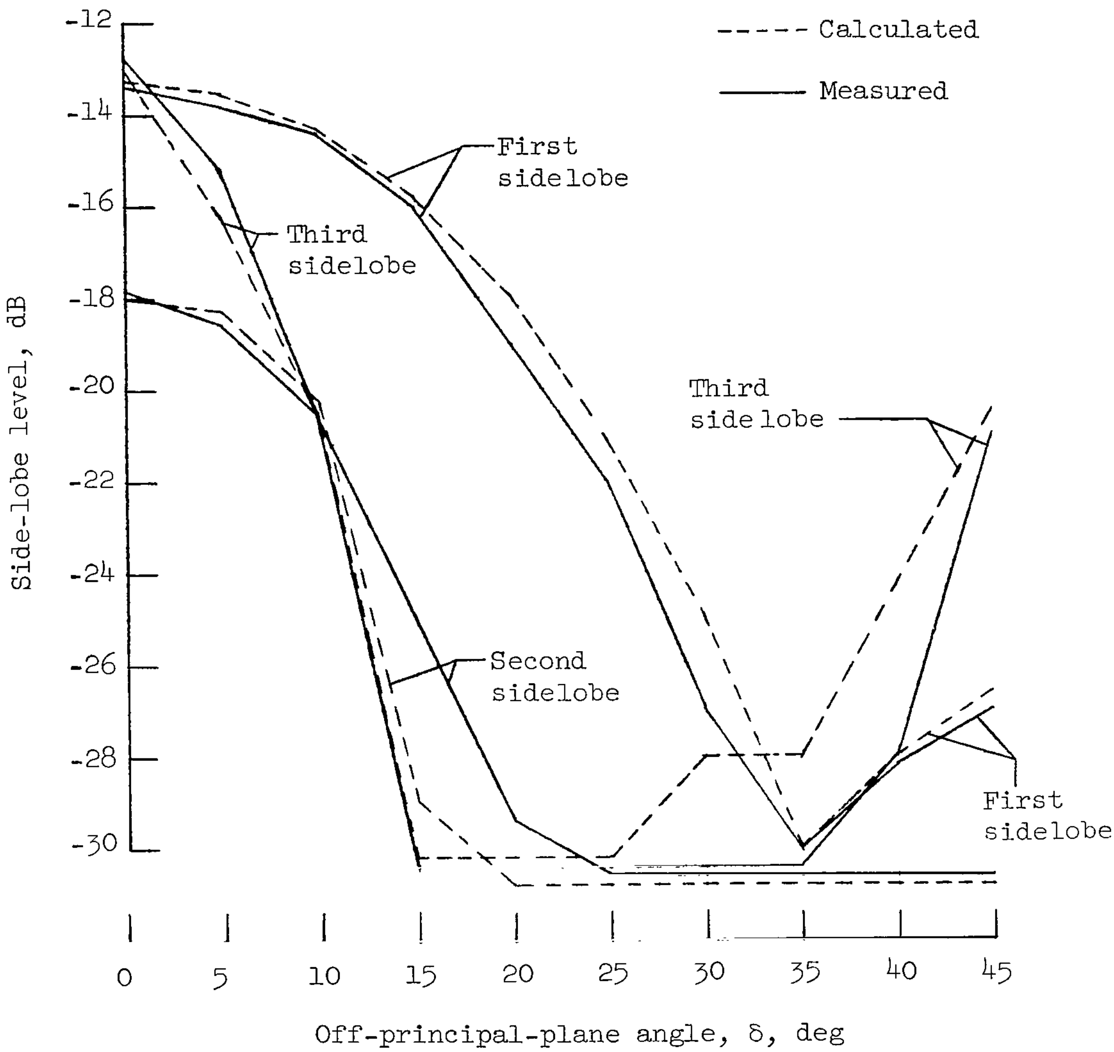


Figure 7.- Off-principal-plane sidelobe amplitude below main beam.

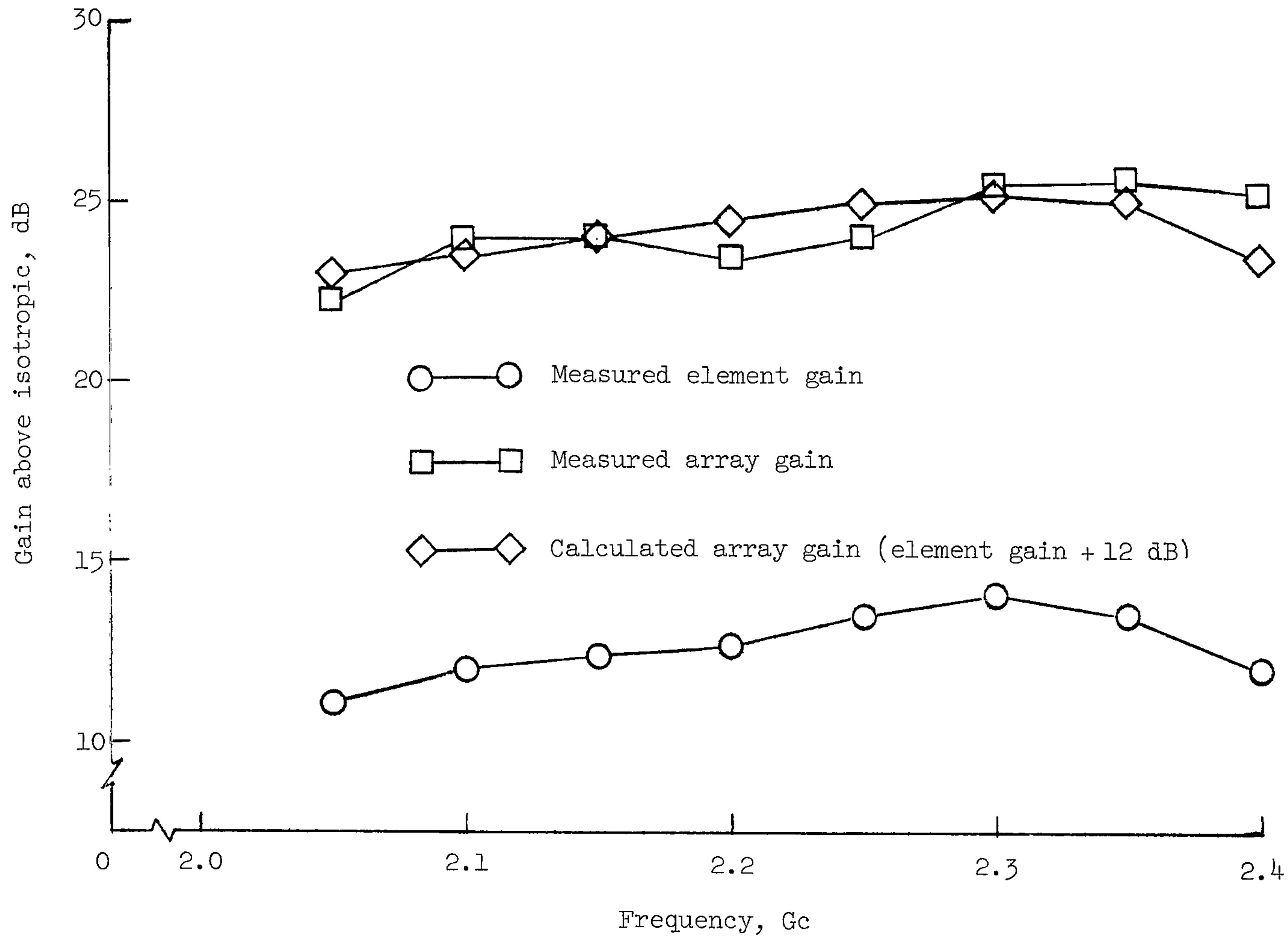


Figure 8.- **Calculated and measured gain of 16-element array (4 by 4).**

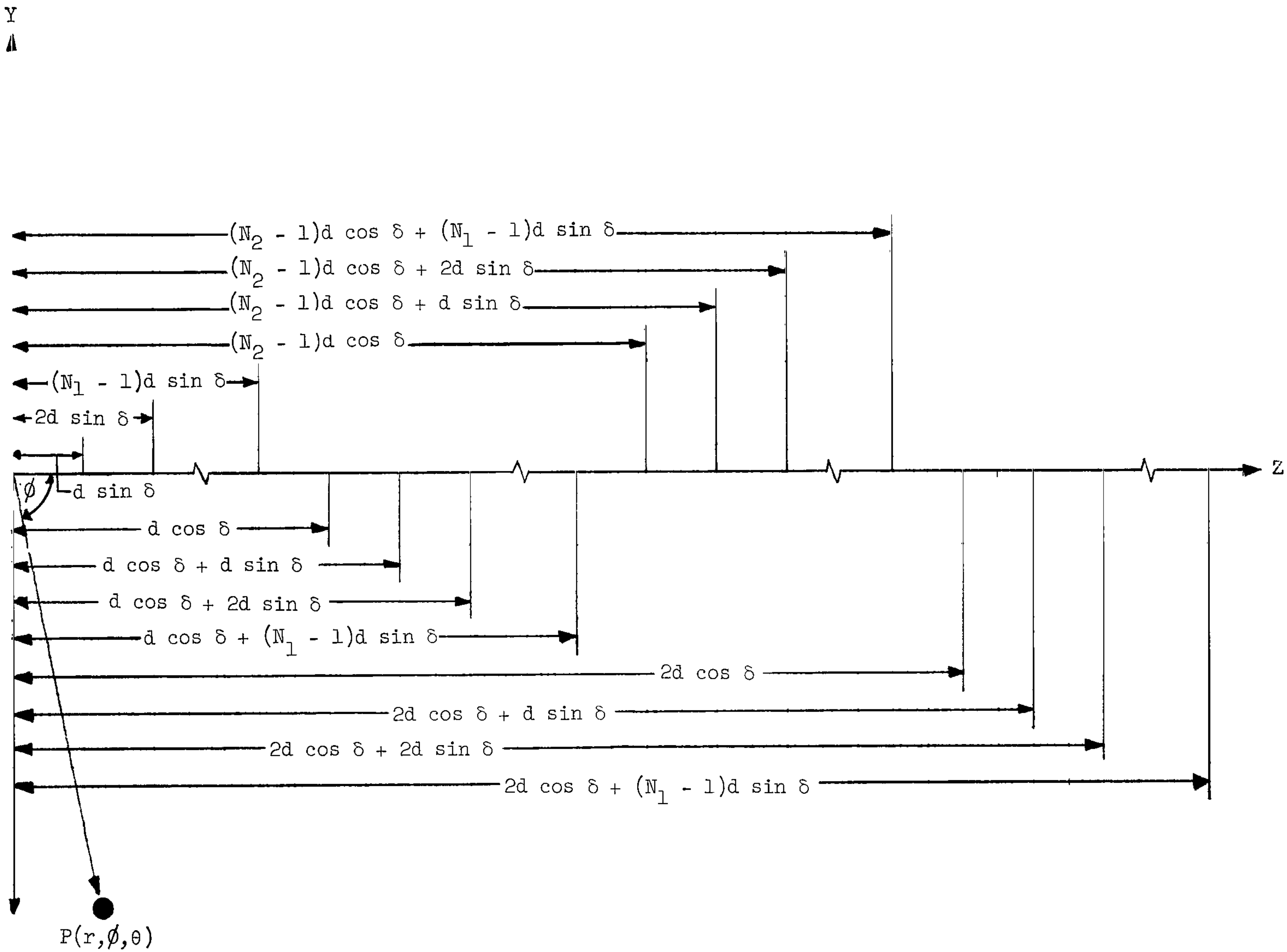


Figure 9.- Projected positions of elements on Z-axis.

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